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MULTI COLUMN CHROMATOGRAPHY SYSTEM

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FIELD OF THE INVENTION

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The present invention relates to a multi-column chromatography system, particularly suitable for high performance liquid chromatography (HPLC). The system optimizes a detector's data gathering ability, such as a mass spectrometer (MS), without sacrificing the quality or quantity of data collected. The system operates via the use of a staggered HPLC-MS operation sequence, through a plurality of individual chromatography systems as directed by a programmed computer protocol, and is suitable for both turbulent flow and laminar flow type systems.

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BACKGROUND OF THE INVENTION

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U.S. Patent No. 5,919,368, owned by the assignee herein, provides an excellent review regarding the utility of separations by high performance liquid chromatography. As noted therein, the separation process relies on the fact that a number of component solute molecules in a flowing stream of a fluid percolated through a packed bed of particles, known as the stationary phase, can be efficiently separated from one another. The individual components are separated because each component has a different affinity for the stationary phase, leading to a different rate of migration for each component and a different exit time for each component emerging from the column. The separation efficiency is determined by the amount of spreading of the solute band as it traverses the bed or column.

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The '368 patent ultimately goes on to describe an improved method of performing liquid chromatography comprising the steps of packing within a tubular container a substantially uniformly distributed multiplicity of rigid, solid, porous particles with

1 chromatographically active surfaces, so as to form a chromatographic column having an
2 interstitial volume between said particles, said particles having average diameters of not
3 less than 30 μm and loading said surfaces with at least one solute that is reactive with said
4 surfaces, by flowing a liquid mixture containing said solute through said column at a
5 velocity sufficient to induce flow of said mixture within at least a substantial portion of
6 said interstitial volume at a reduced velocity greater than about .5000. The
7 aforementioned method: 1. dramatically enhances both the speed and capacity of both
8 analytical and preparative chromatography for both small and large molecules such as
9 biologicals and the like; 2. is operative with mobile phase velocities considerably greater
10 than any previously employed with significantly improved results; 3. makes use of packed
11 particle beds in which the particles are substantially larger than those previously used in
12 the art; and 4. offers a process that is operative at pressures considerably below those
13 taught by the prior art for turbulent flow chromatography. In that regard, attention is also
14 directed to U.S. Patent Nos. 5,772,874; 5,795,469; 5,968,367; 6,110,362 and 6,149,816,
15 also owned by the assignee herein, which disclose other associated methods and
16 apparatus for use in high performance chromatography applications.

17 With the above in mind, attention is now directed to U.S. Patent No. 6,066,848
18 which is said to provide a method and system for analyzing the composition of a plurality
19 of fluid samples by chromatographic techniques. More specifically, the '848 patent states
20 that the invention therein is able to distinguish between each of a plurality of fluid
21 samples simultaneously electrosprayed from parallel liquid chromatography columns
22 towards a mass spectrophotometer such that the mass spectra associated with each fluid
23 sample can be reliably determined. That is, the '848 patent goes on to describe that a

1 plurality of fluid samples are simultaneously separated by parallel liquid chromatography
2 columns and are simultaneously electrosprayed towards an entrance orifice of a mass
3 spectrophotometer. A blocking device having an aperture passing therethrough is
4 positioned so as to block all but one of the fluid samples from passing into the entrance
5 orifice of the mass spectrophotometer at any moment in time.

6 However, various problems have been identified with the above identified
7 technique, which has in various forms be referred to as a "MUX" (i.e. multiplexed) liquid
8 chromatography/mass spectrometry system. For example, such technology generally
9 makes use of one pump to drive four sample streams. As a consequence, it is difficult to
10 achieve optimum pressure in all streams, the back pressure may vary with column
11 packing, the back pressure may vary with use, there can be poor reproducibility between
12 streams, and there is a standing problem of "drift". Expanding upon this, there is no
13 back-pressure monitoring, there is no way to link samples to a specific column, and when
14 a single stream shuts down, e.g., in a four-column system, 25% of the data is lost along
15 with 25% of the samples.

16 In addition, MUX technology, which makes use of a blocking disk, creates a
17 potential for carryover as each spray impinging upon the disk may become cross
18 contaminated. Furthermore, analyte date readout, by virtue of being multiplexed, leads to
19 the feature that each of the electrosprays is analyzed over and over again in sequence.
20 Accordingly, a varying mass spectrum reading will be generated for each of the plurality
21 of fluid sample electrosprays over time. That being the case, MUX analyte data readout
22 will appear as shown in FIGS. 1 and 2 herein, which makes clear that the number of data
23 points is, in all cases, limited by the sampling rate of such a multiplexed system. More

1 specifically, as shown in FIG. 1, data points are a function of sampling rate and are
2 illustrated for sprays 1-4 v. elapsed time. FIG. 2 then illustrates that as a consequence of
3 such multiplexing, the reported peak possibilities are prone to error, as different peaks
4 may be drawn (dotted v. solid line) for the multiplexed data points so collected.

5 Stated another way, the MUX system can lead to insufficient peak data points for
6 tracing along with a sacrifice in precision and sensitivity when operated at faster speeds.
7 Furthermore, such problems are compounded in the case of multiple analytes.

8 Accordingly, there remains a need to develop a multi-column chromatography
9 system that overcomes the disadvantages of the prior art and which provides a more
10 reliable and accurate chromatographic separation along with maximum use of a detector's
11 data gathering ability.

SUMMARY OF THE INVENTION

13 A method and apparatus for chromatographically analyzing each of a plurality of
14 samples in a detector, including an autosampler which contains a plurality of samples for
15 chromatographic analysis, a plurality of chromatography columns, a plurality of pumps
16 associated with said plurality of columns to establish a flow of eluant from each of said
17 plurality of columns and a detector for detecting compounds in said eluant from each of
18 said columns. The apparatus further includes a valve positioned between said detector
19 and said flow of eluant from said columns, said valve permitting each flow of eluant to
20 reach the detector in sequence. A computer control device is included which
21 automatically adjusts the introduction of samples from the autosampler into said plurality
22 of columns as well as the position of said valve to sequentially deliver said eluant to said
23 detector.

1 In alternative embodiment, the present invention relates to an apparatus and
2 method for chromatographically analyzing each of a plurality of samples in detector,
3 comprising an autosampler to contain a plurality of samples for chromatographic analysis
4 and a plurality of chromatographic systems, each system comprising one or more pumps
5 and one or more chromatography columns. A detector is included for detecting
6 compounds in said samples from each of said chromatography systems along with a valve
7 positioned between said detector and said chromatography systems, said valve permitting
8 each sample to reach the detector in sequence and a computer control device which
9 adjusts the introduction of samples from said autosampler into said chromatography
10 systems as well as the position of said valve to sequentially separate and deliver said
11 compounds within said samples to said detector. Each chromatographic system is
12 independent of the others, and each may consist of a number of components, including
13 pumps, columns, valves, and heaters.

14 In a still further embodiment, the present invention relates to a chromatographic
15 system containing a column, including a pump for eluting a mobile phase, and a detector
16 for detecting compounds flowing out of said column, the improvement which comprises a
17 computer control device that: (i) collects pressure readings over time from said pump to
18 provide a tracing, (ii) compares such tracing to a stored pressure v. time tracing for said
19 pump and (iii) elects to shutdown said pump when said tracing deviates from said stored
20 tracing.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 illustrates the prior art analyte read-out for a multiplexed (MUX) HPLC system.

1 **FIG. 2** illustrates the prior art peak measurement possibilities for a multiplexed
2 (MUX) HPLC system.

3 **FIG. 3** illustrates in schematic view the multi-column chromatography system of
4 the present invention.

5 **FIG. 4** illustrates sampling points and peak profile as a result of the multi-column
6 chromatographic system of the present invention.

7 **FIG. 5** illustrates the typical results of the multi-column chromatography system
8 of the present invention.

9 **FIG. 6** illustrates in block diagram format the functionality of the software system
10 protocol of the present invention operating within the computer controller as applied in
11 part to control of the autosampler.

12 **FIG. 7** further illustrates in block diagram format the functionality of the software
13 system protocol of the present invention operating within the computer controller as
14 applied in part to initiate data collection at the detector.

15 **FIG. 8** illustrates in block diagram format the functionality of the software system
16 protocol of the present invention as applied to the monitoring of system pressure.

17 DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

18 One schematic view of the multi-column chromatography system **10** of the
19 present invention is shown in **FIG. 3**. As can be seen therein, the system **10** contains an
20 autosampler which includes a plurality of injection valves **14**, a plurality of pumps **16**, a
21 plurality of columns **18**; a selector valve **20** and a detector **22**. Columns **18** may comprise
22 a wide variety of columns useful for chromatographic analysis which can be used to
23 direct a fluid sample into the entrance orifice of a given detector. For example, columns

1 18 may comprise high performance HPLC columns, capillary electrophoresis columns,
2 gas chromatography columns, flow injection transfer lines, etc. In addition, although not
3 shown, the system may also preferably includes a port valve, positioned before the
4 columns, which in the case of a single column system (one or more pumps and one or
5 more columns) operates to load sample in one direction, and elute in the opposite
6 direction. In the case of a two column system, the port valve provides a similar function,
7 and also provides a loop for eluting solvent.

8 However, as noted above, the present invention may also be described as an
9 apparatus and method for chromatographically analyzing each of a plurality of samples in
10 detector, comprising an autosampler (with preferably two sampling arms) which contains
11 a plurality of samples for chromatographic analysis, along with a plurality of
12 chromatographic systems, each system comprising one or more pumps and one or more
13 chromatography columns. In that regard, it can be appreciated that each chromatographic
14 system is controlled by the computer controller herein to ensure that samples are
15 introduced by the autosampler to avoid overlap at the detector end, and to ensure
16 maximum use of the detector's time as a detector. In that regard, the invention herein
17 preferably relates to the use of, e.g., four (4) independent chromatography systems,
18 wherein each system contains one (1) or more pumps and one (1) or more columns.
19 Alternatively, in a more preferred embodiment, the invention herein relates to the use of
20 four (4) independent chromatography systems, wherein each system contains two (2)
21 pumps and one (1) column, such that one pump is devoted to loading the column with
22 sample, and one pump for elution. As such, the invention herein preferably relates to the
23 use of either of such previously mentioned options, to the extent that at least two (2) of

1 the chromatography systems so defined are incorporated into the sequencing
2 chromatography apparatus of the present invention.

3 As can next be seen in FIG. 4, according to the present invention, the number of
4 data points 24 available in the present invention is consistent with the number of data
5 points available from a standard single-column/single detector configuration. That is, the
6 number and quality of data points 24 from a column chromatography procedure are
7 undisturbed in the present invention, since the present invention relates to the unique
8 sequential operation of a plurality of chromatography systems such that a given point in
9 time such that quality and quantity of data is not sacrificed. As can be seen in FIG. 4,
10 according to the present invention, curve 28 is generated, which represents a more precise
11 curve fitting than that which may be obtained by the multiplexed system of the prior art,
12 which inherently contains fewer data points as well as the possibility to report less precise
13 curve 26. In that regard, it is worth noting that no matter how fast a multiplexed system
14 is sampling, the invention herein will, e.g., in case of a four (4) samples to be analyzed,
15 report four times more information (data points) for any given peak.

16 Expanding upon the above, attention is directed next to FIG. 5, which illustrates
17 curves 30, 32, 34, and 36, as obtained herein, due to procedural benefit of controlled
18 staggered/sequenced injections. As can be seen, the detector analyzes each curve in
19 sequence. In such regard the detector herein functions to detect and report curve 30,
20 while those samples responsible for curves 32, 34, and 36, although in the process of
21 being eluted in the column, have not yet exited from the column. Such programmed
22 chromatography sequencing is provided herein by a computer control device which, upon
23 consideration of when the target sample is likely to exit the column, adjusts the

1 introduction of samples from the autosampler into the columns to sequentially deliver
2 eluant containing sample for sequenced detection. In other words, the computer
3 controller herein considers the samples in the autosampler, and the input of information
4 concerning their anticipated data-collecting window at the detector, and selects those
5 samples from the autosampler for introduction into the system to maximize detector use.

6 The computer control device of the present invention therefore adjusts the
7 introduction of sample from the autosampler, as well as the position of valve 20 (FIG. 3)
8 to sequentially deliver eluant to the detector. However, the computer control device
9 herein preferably functions to provide other important blocks of information to the user.
10 This is more specifically illustrated in FIG. 6, which provides a schematic overview of
11 the functionality of the software system protocol within the computer control device of
12 the present invention as applied to the autosampler. As shown therein, the control device
13 first checks that the autosampler/probe is ready to start a sample and that sufficient time
14 has passed since the last sample start. The controller then checks that a chromatographic
15 system as herein defined is ready to accept a sample. This is determined by the time
16 remaining for the currently running elution protocol, and this prediction therein optimizes
17 the overall system efficiency. By contrast, waiting for the chromatography system to
18 indicate that it is "ready" before starting the sample would elongate the cycle time by that
19 amount of time between starting the sample and the sample being "ready" to inject.

20 The controller then determines which sample corresponds with the "ready"
21 chromatography system. When sample information is entered, the user has the option of
22 specifying a particular chromatography system or allowing any of the available systems to
23 be used for the sample. The sample is then started and when the sample is ready to inject,

1 the controller will verify that the chromatography system is ready and that injection will
2 not cause the new data window (i.e., the ensuing report of the chromatographic peaks) to
3 overlap the previously injected sample data windows.

4 **FIG. 7** illustrates the detector and selector valve control of the present invention.
5 As shown therein, the controller checks that a chromatographic system elution protocol
6 ("method") has progressed to the start "data window time" as specified by the current
7 method. The selector valve is then moved to deliver the fluid stream of the
8 chromatographic system to deliver sample to the detector and the detector is signaled to
9 begin data collection.

10 **FIG. 8** illustrates the pressure control of the invention herein as provided by the
11 computer controller. More specifically, the controller will collect back pressure readings
12 for each pump 14 in each chromatography system at an average rate of 10 data points per
13 second. As noted above, the chromatography system herein refers to one or more pumps
14 and one or more chromatography columns within the disclosed chromatography
15 apparatus.

16 The computer controller therefore maintains a running average for the pressure for
17 each pump in each system. The controller then compares that running average to a
18 history for that pump in each system and determines whether or not deviation exists that
19 would warrant a shutdown. In a related manner, the controller maintains a running
20 average for the pressure for each type of pump in the system, i.e., loading pumps or
21 eluting pumps. The controller again compares that running average to a history for that
22 pump in each system and again determines whether or not deviation exists that would
23 warrant a shut-down.

1 The controller herein also compares each newly collected sample to the average of
2 pressure for that pump for the previous run. The controller then generates offset and
3 correlation data for that newly collected sample. In other words, the controller identifies
4 whether or not the data points vary in intensity and location (i.e., that point in time) from
5 the average pressure v. time tracing generated from one or more previous runs. The
6 controller then determines whether or not the generated offset and correlation values or
7 tracings are within acceptable limits. In a preferred embodiment, when the generated
8 pressure v. time tracing deviates from the stored tracing by, e.g. the slope or shape of the
9 tracing between at least two pressure readings, the system may be shutdown.

10 In addition, and in related context, the controller also compares each new
11 collection of sample back-pressure data points for a given pump to the running average
12 based upon pump type. Once again, the controller generates offset and correlation data,
13 and determines whether or not the generated offset and correlation values are within
14 acceptable limits. If offset and correlation values for the pump are outside of a user
15 selected range, sample introduction into the system is suspended.

16 Finally, if offset and correlation values for a given system are outside of user
17 selected ranges when compared to other chromatography systems (when such other
18 systems are running the same sample and elution protocol) sample introduction on the
19 system will also be automatically suspended.

20 One particularly preferred column herein, but by no means limiting, are those
21 columns which include a substantially uniformly distributed multiplicity of rigid, solid,
22 porous particles with chromatographically active surfaces, said particles having average
23 diameters of greater than about 30 μm , the interstitial volume between said particles

1 being not less than about 45% of the total volume of said column; and means for loading
2 said surfaces with at least one solute that is reactive with said surfaces, by flowing a
3 liquid mixture containing said solute through said body at a velocity sufficient to induce
4 flow of said mixture within at least a substantial portion of said interstitial volume at a
5 reduced velocity greater than about 5,000.

6 To these ends the present invention is directed to the use of a chromatography
7 column or body in the sequenced chromatography system herein that is formed as a
8 substantially uniformly distributed multiplicity of rigid, solid, porous particles having
9 substantially uniform mean cross-section dimensions or diameters of not less than about
10 30 μm , typically 50 μm or greater up to, but not limited to, 1000 μm in certain instances
11 as will be delineated hereinafter. The term "particle" as used herein should not be
12 construed as limited to any particular form or shape, regardless of symmetry or lack
13 thereof, aspect ratio, regularity and the like. The term "solid" as used herein, is intended
14 to refer to the physical state of the matter and should not be construed to exclude porous
15 particles. The particles are selected from a range of various sizes and shapes and are held
16 together in a body or column as by pressure, sintering and the like so that interstitial
17 channels having a total interstitial volume of not less than about 45% of the total volume
18 of the column are formed between the particles. The surfaces of the particles, including
19 the inner surfaces of the pores in the particles, may be chromatographically active, as by
20 being coated with chromatographic stationary phase layers. This method includes the step
21 of flowing through the column a fluid mixture containing at least one solute or suspended
22 phase that is interactive with the particles' surfaces in order to load the column. Because
23 of the nature of the particles and packing in the column, the flow of the fluid mixture

1 through the column can be at a high flow rate, preferably at an average reduced velocity
2 (i.e., $ud[p]/D$ wherein "u" is the mobile phase velocity, "d[p]" is the packing particle
3 diameter and "D" is the diffusion coefficient in the mobile phase) greater than about
4 5000, and including, in certain instances to be described hereinafter, reduced velocities
5 values as high as 70,000 or higher. It is believed that under such conditions, turbulent
6 flow of the mixture is induced within at least a major portion of the interstitial volume,
7 and it is postulated that such turbulent flow in fact enhances the rate of mass transfer, thus
8 increasing the dynamic capacity of the column.

9 The particles described above are preferably formed from materials that are
10 incompressible, which term is to be understood to mean that the time rate of changes of
11 the densities and volumes of the particles under pressures of at least about 5×10^3 psi,
12 (including outlet column frit retainer) remains substantially zero, and the particles
13 therefore will substantially resist plastic deformation even at such high pressure. The
14 particles are shaped and selected in a range of sizes and shapes such that they can be
15 packed at a pressure sufficient to form a column characterized in having interstitial
16 channels formed between the particles. Because of the irregularity of the particles, it will
17 be recognized that the interior walls of such channels are necessarily quite rough in
18 configuration. While it is believed that at least the majority of channels have mean cross-
19 section diameters substantially not less than about 4 μm , the interstitial volume fraction
20 (i.e. the total volume of interstitial channels between the particles) should not be less than
21 about 45% of the total volume of column. It will be appreciated that typical columns have
22 interstitial volume fractions less than about 45%, more particularly ranging from about
23 35% to 42%. The surfaces of particles are chromatographically active either per se as is

1 well known in the art, or by treatment, as by coating, with any of the many known
2 chromatographically active, stationary phase layers, also as well known in the art.

3 As noted, in order to insure the formation of the desired uniform density column
4 with the preferred interstitial fraction and preclude collapse under operating pressure, the
5 particles used to pack a column for use in the present invention of sequenced
6 chromatography analysis may include rigid solids that must necessarily be incompressible
7 at packing pressure of at least about 5×10^3 psi, preferably up to pressures as high as
8 about 1×10^4 psi. To that end, the preferred particles are formed from materials such as
9 alumina, titania, silica, zirconia, vanadia, carbon, various relatively inert metals, and
10 combinations thereof.

11 In that regard, the chromatography column used herein may include columns used
12 under conventional laminar flow regimes. The columns may therefore be constructed of
13 particles, which due to a lack of requisite rigidity are run at low flow rates and pressure
14 drops. Such particles may have average particle sizes less than about 30 microns and as
15 small as about 1 micron. It is understood that under these operating conditions, the
16 analysis times are relatively long and the reduced velocities may be as small as 1.

17 In addition, the invention herein may include the use of a substantially uniform,
18 elongated chromatography column containing chromatographically reactive surfaces,
19 means for injecting into said column a discrete volume of liquid mixture containing at
20 least one solute that is reactive with said surfaces so as to load said column, and means
21 for flowing eluant fluid through said loaded column, wherein the means for flowing said
22 eluant fluid comprises means for injecting at least one discrete plug of said eluant fluid
23 into said column adjacent the input of said column so as to maintain minimized spatial

1 step separation between said plug and said discrete volume of liquid mixture as said plug
2 and volume traverse the column wherein said column and said means for flowing are
3 configured such that the flow of said volume of eluant traverses said column at a reduced
4 velocity greater than about 5000.

5 The invention herein is also applicable to chromatography columns having
6 chromatographically reactive surfaces, including the steps of flowing through said
7 column a discrete volume of a liquid mixture containing at least one solute that is reactive
8 with said surfaces, and eluting from said surfaces said solute bound thereto, by flowing
9 eluant fluid through said column, comprising the steps of injecting at least one discrete
10 volume of an eluant fluid into the flowstream in said column such as to maintain
11 minimized spatial separation between said discrete volumes as the latter traverse said
12 column at a reduced velocity great than about 5,000.

13 The invention herein is also applicable to separating relatively low molecular
14 weight compounds from compounds having relatively high molecular weights
15 substantially an order of magnitude greater or more than said low molecular weight
16 compounds in a liquid mixture of said compounds, comprising a chromatographic body
17 formed of substantially uniformly distributed multiplicity of rigid, solid, porous particles
18 with average diameters of not less than about 30 μm , and average pore diameters
19 sufficiently small to substantially exclude introduction of said compounds of relatively
20 high molecular weight into said pores, the surfaces of said particles and pored being
21 hydrophobic and chromatographically active, and a means for flowing said mixture at a
22 velocity sufficient that the flow of said mixture within at least a substantial portion of the
23 interstitial volume between said particles is at a reduced velocity greater than about 5,000

1 until said high molecular weight compounds have exited said body, and a means for
2 eluting said relatively low molecular weight compounds from said body with an eluant
3 liquid at a reduced velocity less than about 5,000, after said high molecular weight
4 compounds have exited from said body.

5 With consideration now shifted to the detector 22, such is preferably any type of
6 detector that is employed in chromatography systems to detect the samples eluted through
7 the columns. Those skilled in the art will therefore recognize that detector 22 may
8 comprise an ultraviolet detector, or more preferably, a mass spectrophotometer. The
9 detector therefore provides identification of the desired component compounds of a
10 sample by determining exactly when such a desired component compound is eluted from
11 the exit end of the column.

12 The invention herein is suitable for any type of chromatography type configuration
13 making use of a multiple column configuration. In that regard, the invention herein is
14 applicable to analytical chromatography as well as preparative chromatography systems.
15 In that regard, the invention is applicable herein to conventional HPLC systems relying
16 upon a mass spectrometer detector which system undergoes conventional programmed
17 liquid flow velocities and makes use of conventional type gradient systems. However,
18 while such use of conventional chromatography systems is suitable herein, the invention
19 herein advances the efficiency of such known systems by uniquely linking up a plurality
20 of such systems to a single detector to optimize the detectors data gathering ability
21 without sacrificing the quality or quantity of data collected.

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